THE JOINT AEROSOL–MONSOON EXPERIMENT

A New Challenge for Monsoon Climate Research

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Understanding the physical processes responsible for aerosol–monsoon water cycle interactions is fundamental to improving prediction and enhancing vigilance of climatic hazards in the Asian monsoon region.

Smoke consisting of mixtures of dust and industrial pollution covering the Forbidden City, Beijing, China.

Air pollution and monsoon floods and droughts are two of the most serious environmental threats to over 60% of the world population living in Asia. The increasing aerosol loading in Asian countries associated with industrialization during the last two decades has caused major health-related problems associated with worsening air quality and has also impacted aviation safety. Recent field experiments over the South Asian (Ramanathan et al. 2001) and East Asian (Conant et al. 2003; Li et al. 2007a) regions have found that anthropogenic aerosols may significantly change the energy balance of the atmosphere and at the Earth's surface. General circulation model (GCM) studies have suggested that anthropogenic aerosol forcing could influence the seasonal rainfall distribution in the monsoon regions over South (Ramanathan et al. 2001, 2005; Chung et al. 2005) and East Asia (Menon et al. 2002). Others have demonstrated the importance of the atmospheric heating by elevated absorbing aerosols (dust and black carbon) in spurring anomalous water cycle feedback, affecting the general circulation and altering the radiation and dynamical states of the entire monsoon system (Lau et al. 2006; Lau and Kim 2006).

To address the scientific issues of elevated aerosols and their interaction with the large-scale monsoon circulation, the international workshop "Effects of Elevated Aerosols on the Radiation and Dynamics of the Monsoon Water Cycle" was held during 31 July–4 August 2006, in Xining, Qinghai–Tibetan Plateau, China. The workshop was cosponsored by the Coordinated Enhanced Observation Program (CEOP) under the Global Water and Energy Experiment/World Climate Research Program (GEWEX/WCRP) and the National Natural Science Foundation of China. Attendees include international experts on aerosol, radiation, and monsoons, and representatives from government agencies from China, India, Italy, Japan, and the United States. At the workshop, participants exchanged the latest scientific findings on aerosol and monsoon research and provided updates on a number of related national research programs in China, India, Japan, Italy, and the United States and their connections with international programs. This article describes the scientific rationale and the challenges of studying aerosol–monsoon water cycle interaction and outlines a proposal for joint aerosol–monsoon research, based on recommendations by the workshop participants, as well as follow-up discussions with interested scientists.

BACKGROUND. Long recognized as a major regional environmental hazard in causing severe health problems and problems in aviation safety, aerosols are now known to have strong impacts on both regional and global climates. It has been estimated that aerosol may reduce by up to 10% of the seasonal mean solar radiation reaching the Earth's surface at various regions of the globe, producing a global cooling effect that masks the global warming (Ramanathan et al. 2001; Chung et al. 2005). This means that the potential perils that humans have contributed to global warming may be far greater than what we can detect or have detected at the present. Aerosols in the form of tiny suspended particles in the atmospheres intercept solar radiation reaching the Earth's surface and interact strongly with the processes of formation of clouds and rain. However, much of aerosol–cloud–precipitation interaction processes are still not well understood. As a result, aerosol and cloud processes are poorly represented in climate models and they have been recognized as major sources of uncertainties in future climate projections (Houghton et al. 2001).

In recent years, in Asian monsoon countries, such as China and India, the aerosol problem is becoming increasingly acute, especially in large cities and rural areas due to the increased loading of atmospheric pollutants from waste gas emissions and from rising energy demand associated with the rapid pace of industrialization and modernization. On the other hand, sustainable development in the Asian monsoon countries depends on the vagaries of the mighty monsoon, which supplies almost all the freshwater for the region. Uneven distribution of monsoon rain associated with flash flood or prolonged drought has caused major loss of human lives and damages in crops and properties, with devastating societal impacts on Asian countries. It is well recognized that pollution problems are exacerbated by stable atmospheric conditions, such as subsidence and formation of the inversion layer during the dry premonsoon seasons, or during monsoon break periods, and that during the monsoon season, heavy rain can wash

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out aerosols and clean the air. Recent studies have suggested that aerosol in the atmosphere can affect the monsoon water cycle by significantly altering the energy balance in the atmosphere and at the Earth's surface (Ramanathan et al. 2001; Li 2004) and by modulating cloud and rain processes (Rosenfeld 2000; Menon et al. 2002; Ramanathan et al. 2005; Lau et al. 2006, and others).

THE SCIENTIFIC RATIONALE. Up to now most aerosol studies have been focused on the radiative, microphysical, and chemical aspects of aerosols and interactions with clouds and precipitation on localized spatial and temporal scales under conditions where atmospheric dynamic controls are relatively weak or unchanged. From a global perspective, the combined effects of aerosols from local sources and from transport processes occurring in different parts of the globe and in different seasons are likely to alter the large-scale heating and pressure gradients and induce changes in the atmospheric general circulation, affecting the processes of generating clouds and rainfall. The anomalous diabatic heating from rainfall and clouds may further drive the regional or global circulation, which could in turn alter aerosol properties and distribution, providing feedback to the local effects.

Given the large number of variables that controls aerosol sources and transport, the diverse physical and chemical properties of aerosols, and possible feedback to the atmospheric general circulation, interactions of aerosol and the regional and global water cycles are extremely complex. Based on the presentations and discussions at the Xining workshop, the dominant pathways that aerosols and the water cycle may interact with the large-scale circulation are illustrated schematically in Fig. 1. Aerosols scatter and/or absorb solar radiation, thus cooling the Earth's surface, that is, the direct effect. The reduction of solar radiation at the surface is referred to as the "solar dimming" effect. Because of the diverse distribution of sources of natural (dust, wild fire, biogenic emissions, volcanic eruption, and sea salt) and anthropogenic (fossil fuel and biofuel combustions and anthropogenic biomass burning) aerosols in space and time, and because of the long-range transport of fine aerosol particles, solar dimming is global in extent (Stanhill and Cohen 2001). Since the Earth's surface cools more than the atmosphere above it, the surface cooling may stabilize the lower troposphere, thus limiting convection, that is, the semidirect effect (Hansen et al. 1997; Ackerman et al. 2000).

Another way aerosol can affect the water cycle is through interaction with cloud microphysical processes, whereby aerosol increases the number of cloud condensation nuclei (CCN) forming smaller water droplets that increase scattering cross sections, brightens clouds, and reflects more solar radiation—the first indirect effect (Twomey 1977). The small droplets limit collision and coalescence, prolonging the lifetime of clouds and inhibiting the growth of cloud drops to raindrops—the second indirect effect (Albrecht 1989; Rosenfeld 2000). This leads to more clouds, increased reflection of solar radiation, and further cooling at the Earth's surface. It is also possible that, in an environment of increasing atmospheric moisture and buoyance, an increase in hygroscopic aerosol may activate more CCN and accelerate droplet growth by diffusion and collision, increasing rainfall (Li and Yuan 2006). Additionally, dust aerosols have been shown to act as giant ice nuclei in initiating ice-phase precipitation at high altitudes, thus favoring deep convection and increased rainfall (Sassen 2002). All these local processes may contribute to changes in

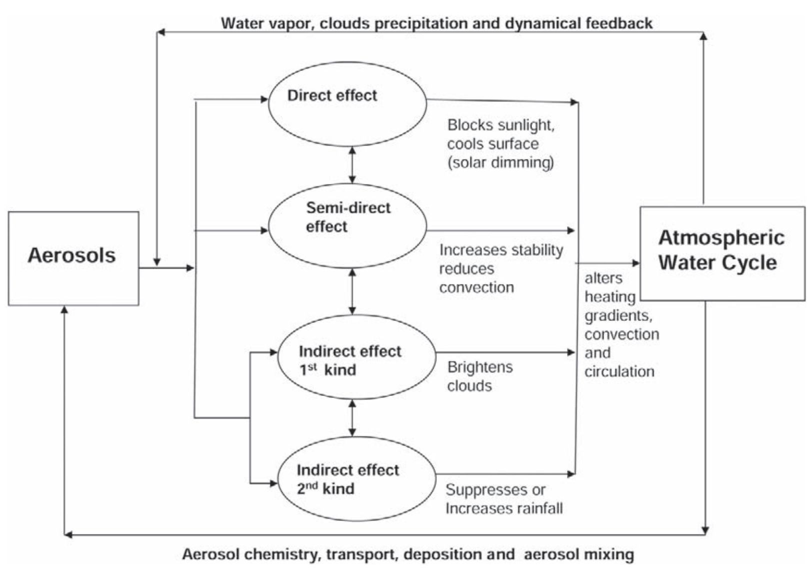

Fig. 1. Schematic interaction pathways for aerosol local forcing (direct, semidirect, and indirect effects), response, and feedback by the atmospheric water cycle, (upper return path) through clouds, precipitation, and large-scale circulation, and (lower return path) through aerosol transport, chemistry, deposition, and aerosol–aerosol interaction.

heating gradients in the atmosphere and at the Earth's surfaces (see Fig. 2; Chung et al. 2005; Ramanathan et al. 2001), which drive an anomalous (relative to the mean state) large-scale circulation. The anomalous atmospheric state caused by feedback with the water vapor, cloud, and precipitation processes may cause further changes in the aerosol forcing function (as shown in the upper feedback path in Fig. 1). In addition, the anomalous large-scale circulation is likely to change the aerosol transport, modulate dry and wet deposition processes, and alter the physical and chemical environments in which mixing of different aerosol species may take place (see lower feedback pathway in Fig. 1). The chemical transport processes may then lead to redistribution of the aerosol concentration and aerosol properties and further alter the aerosol local forcing functions. The complex interaction pathways shown in Fig. 1 call for an Earth system approach to the problem of aerosol–water cycle interaction, requiring understanding of local and global processes, physical and chemical properties, and microphysical and dynamical controls governing the interactions of aerosols and clouds and precipitation processes.

In the Asian monsoon and adjacent regions, the aerosol forcing and responses of the water cycle are especially complex. Dust transported by the large-scale circulation from the adjacent deserts to India, sulfate and black carbon from industrial pollution in central southern China and northern India, and organic and black carbon from biomass burning from Indo-China may contribute to variability in differential heating and cooling of the atmosphere and to the land–sea thermal contrast (see discussion for Fig. 2). The magnitude of the total aerosol forcing due to sulfates and soot have shown to be quite large corresponding to a surface radiative cooling of 20–40 W m^{-2} over the Asian monsoon land in the premonsoon season (D. Sikka 2006, personal communication). However, the detailed spatial and temporal distributions of the forcing from different species of aerosols and their combined effects on monsoon climate variability are not well known. Studies conducted up to now have suggested that aerosol radiative forcing may influence regional climate and the monsoon water cycle via the interplay of four major interacting mechanisms.

The solar dimming effect. This refers to the surface cooling due to the shielding of solar radiation from reaching the Earth's surface by aerosols known as atmospheric brown clouds (ABCs). ABCs are characterized by layers of air pollution consisting of black carbon, organic carbon, fly ash, and dust that absorb and scatter solar radiation, as well as other anthropogenic aerosols, such as sulfates, which scatter solar radiation (Ramanathan and Crutzen 2003). The ABCs exert SDM and atmospheric heating effects globally, with similar spatial patterns and comparable magnitudes, suggesting a large redistribution of energy between the atmosphere (Fig. 2a) and the Earth's surface (Fig. 2b). The forcings are highly nonuniform, with large spatial gradients with largest magnitudes (<15–20 W m^{-2}) over the major monsoon regions (South Asia, East Asia, the Maritime Continent, West Africa, South America, and Mexico) due to the

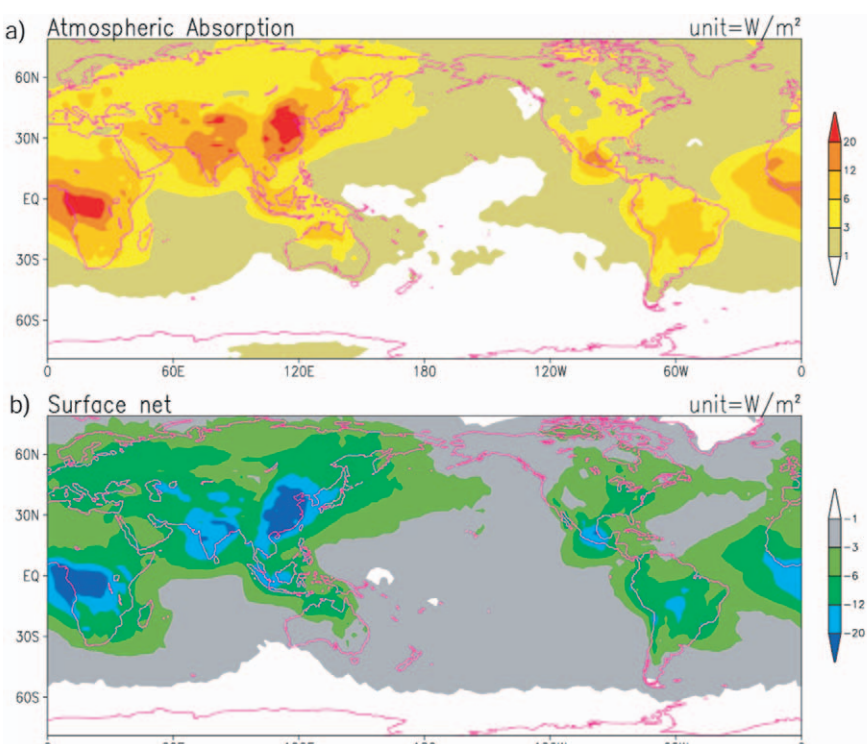

Fig. 2. Estimate of annual mean (a) atmospheric heating and (b) solar dimming due to global distribution of aerosol for the period 2000–03 based on MODIS, AERONET observations, and the Goddard Chemistry Aerosol Radiation Transport (GOCART) model output (from Chung et al. 2005).

combination of desert dust, smoke, and black carbon from biomass burning and sulfate and soot from industrial and biofuel pollutions. As shown in Fig. 2, the magnitude of aerosol-induced differential heating (cooling) of the atmosphere (surface) between the Asian monsoon land and the adjacent oceans is of the order of at least 10–20 W m^{-2}.

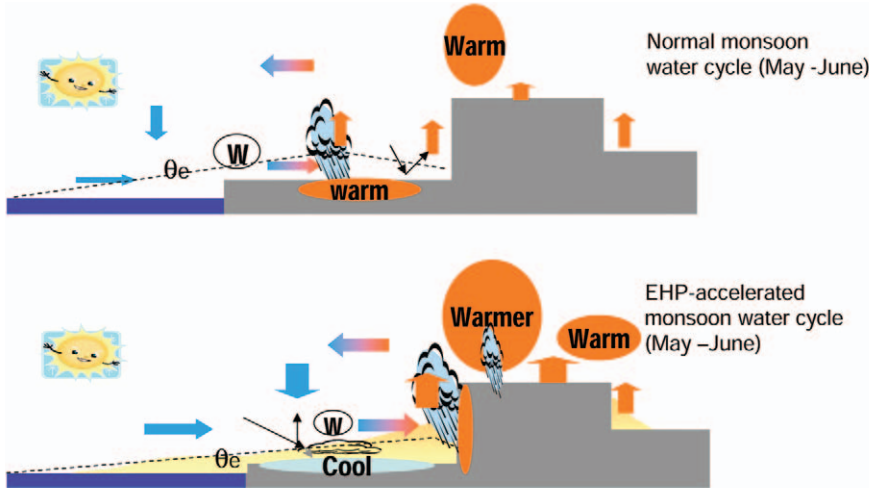

FIG. 3. Schematic showing the monsoon water cycle (top) with no aerosol forcing and (bottom) with aerosol-induced elevated heat pump effect. Low-level monsoon westerlies are denoted by W. The dashed line indicates magnitude of the low-level equivalent potential temperature θ_e. Deep convection is indicated over regions of maximum θ_e. (See text for further discussions.)

Ramanathan et al. (2005) showed from fully coupled ocean–atmosphere GCM experiments that the SDM effect at the surface due to the inclusion of ABC aerosol forcing causes a reduction in surface evaporation, a decrease in meridional sea surface temperature (SST) gradient and an increase in atmospheric stability, and a reduction in rainfall over South Asia. In addition, because of the higher concentration of ABCs over the Northern Hemisphere oceans, compared to the Southern Hemisphere oceans, more cooling occurs in the former, resulting in a weakening of the summertime global-scale meridional overturning, which weakens the South Asian monsoon. In their coupled ocean–atmosphere experiments, which account for increases in greenhouse gases, Ramanathan et al. (2005) also found that the ABCs could have masked as much as 50% of the surface warming due to the increase in greenhouse gases and speculated that drought frequencies may increase over the Indian subcontinent in coming decades. The SMD effect over land is consistent with in situ observations, for example, at a site near Beijing, the reduction by aerosols of annual and daily mean solar radiation reaching the surface is estimated to be 20–24 W m^{-2}, more than half of the reduction induced by clouds and about 6 times the effect of doubling CO_2 (Li et al. 2007b). We note, however, that there remain large uncertainties in observational capability and our understanding of the aerosol forcing due to ABCs and their interaction with the monsoon. These recent modeling and observational studies have provided the motivation for improving our understanding of aerosol–monsoon interactions.

The "elevated heat pump" effect. Recently, Lau et al. (2006) examined the direct effects of aerosol on the monsoon water cycle variability from GCM simulations with prescribed realistic global aerosol forcing and proposed the EHP effect, suggesting that atmospheric heating by absorbing aerosols (dust and black carbon), through water cycle feedback, may lead to a strengthening of the South Asia monsoon. The essence of the EHP effect is illustrated schematically in Fig. 3. Figure 3 (top) shows the atmosphere–ocean–land conditions around the time of the onset of the monsoon, which includes the development of low-level westerly flow over central India; appearance of deep convection over regions of high convective available potential energy, indicated by maximum low-level equivalent potential temperature θe; heating over the Indian subcontinent; and related elevated heat sources provided by the Tibetan Plateau. Figure 3 (bottom) illustrates possible changes in rainfall, clouds, and the monsoon water cycle when effects of absorbing aerosols are included.

The EHP effect as diagnosed in the GCM experiments in Lau et al. (2006) is summarized as follows. Dusts mixed with black carbon aerosols over the Indo-Gangetic Plain (IGP) that accumulate over the foothills of the Himalayas in April and May provide an elevated heat source through absorption of solar radiation, causing the air above the Himalayas slope to heat up. As the air warms, it rises over the southern escarpment of the Tibetan Plateau, drawing in more warm and moist low-level air from the Indian Ocean as the monsoon season approaches. Because of the surface cooling due to aerosol absorption over central India, rainfall is suppressed due to the semidirect effect. As a result, the moist air is able to penetrate farther inland to the foothills of the Himalayas, producing anomalous rainfall there. The increased condensation causes more upper-tropospheric heating, which draws in more low-level moist air from the ocean, producing a positive feedback effect.

Among the key postulates of the EHP hypothesis are a) absorbing aerosol induces through water cycle feedback positive upper-tropospheric temperature anomalies over the Tibetan Plateau, and b) monsoon rain begins earlier in May through June in northern India and the southern Tibetan Plateau, with a c) subsequent increase of the monsoon rainfall over entire India in July–August, and d) a corresponding reduction in rainfall in the northern Indian Ocean. The EHP effect essentially accentuates the seasonal heating of the Tibetan Plateau, whose impacts on the onset and evolution of the monsoon is well known (Meehl 1994; Yanai et al. 1992; Wu et al. 1997, 2004; Wu and Zhang 1998; Hsu and Liu 2003, and others). Recently, Lau and Kim (2006) have found in observations the presence of strong atmospheric heating associated with the formation of a large-scale anomalous upper-tropospheric anticyclone over the southern portion of the Tibetan Plateau in May–June, following major episodes of enhanced absorbing aerosols in the IGP in April–May, consistent with the EHP effect. Recent experiments with the National Center for Atmospheric Research (NCAR) atmospheric GCM also show that black carbon aerosol may lead to strengthening of the South Asian monsoon (Meehl et al. 2008). The EHP is a working hypothesis that rests on specific assumptions regarding aerosol types, horizontal distribution, depth, and elevation and radiative properties, all of which need to be validated by more detailed observations and further numerical experiments to test the sensitivity to aerosol forcing.

The aerosol microphysics effect. As mentioned above, in the premonsoon months of April–May, the dominant type of aerosol in the IGP of India over the southern edge of the Tibetan Plateau appears to be mineral dust, transported mostly from the deserts in western India, Pakistan, and the Middle East. At the same time, over the northern edge of the Tibetan Plateau, dust storms frequently occur over the arid and semiarid regions of northwestern China. The large-scale circulation is important in transporting the dust over large areas of the Asian continent, affecting the interaction of local pollutants with the regional water cycle.

During episodes of increased pollution in the premonsoon season, bright clouds are often seen to form over the polluted IGP, compared to the relatively clean cloud over the Tibetan Plateau (Fig. 4, top). At the same time, the Moderate Resolution Imaging Spectroradiometer (MODIS) images showed higher values of aerosol optical thickness (AOT) (Fig. 4, bottom left), but a smaller effective cloud radius of less than 10 μm (Fig. 4, bottom right) over the regions of the polluted clouds. These observations provide hints to the presence of aerosol indirect effect. The MODIS standard algorithms for estimating AOT and radiative forcing in Fig. 4 have quantitative uncertainties over bright surfaces, especially with overlapping layers of aerosols and clouds. However, the improved "Deep Blue" algorithm (Hsu et al. 2004) in the latest version of the MODIS data has overcome this problem.

Up to now, studies of microphysical effects of pollution on monsoon climate have been focused on the nonrainy seasons, that is, boreal winter or fall, where strong local inversion induced by the subsiding air makes the pollution problem more acute. Few studies of aerosol indirect effects have been devoted to the summer monsoon rainy season. Yet, it is possible that a preconditioning of the cloud system by aerosol microphysics effects prior to monsoon onset or during monsoon breaks may interact with the SDM and EHP effects, further affecting the subsequent evolution of the monsoon water cycle. If the aerosols consist of mostly fine-mode industrial pollution, in an environment where the liquid water content of the atmosphere remains unchanged, they will increase the number density of CCN and suppress rainfall. On the other hand, if the liquid water content is increased due to change in meteorological conditions, rainfall may be enhanced (Li and Yuan 2006). Further if the aerosols consist primarily of coarse-mode particles from dusts, they may promote ice nucleation and lead to more frequent outbreaks of deep convection in periods leading up to the monsoon onset. Additionally, in the presence of anthropogenic aerosols (e.g., sulfate, black carbon, etc.) the larger dust particles may act as effective aerosol scavengers sweeping up the smaller-size anthropogenic aerosols. These aggregate dust–soot mixtures could potentially absorb much more solar radiation in the atmosphere than by either dust or soot alone and thus exert stronger forcing in the radiative energy balance in the earth–atmosphere system (Ramanathan et al. 2001).

Coupled atmosphere–ocean–land interactions. Ultimately, how aerosols affect the entire monsoon system will depend on the interaction of all the aforementioned processes and how they interact with forcing from sea surface temperature and land surface processes. In recent numerical experiments, Chung

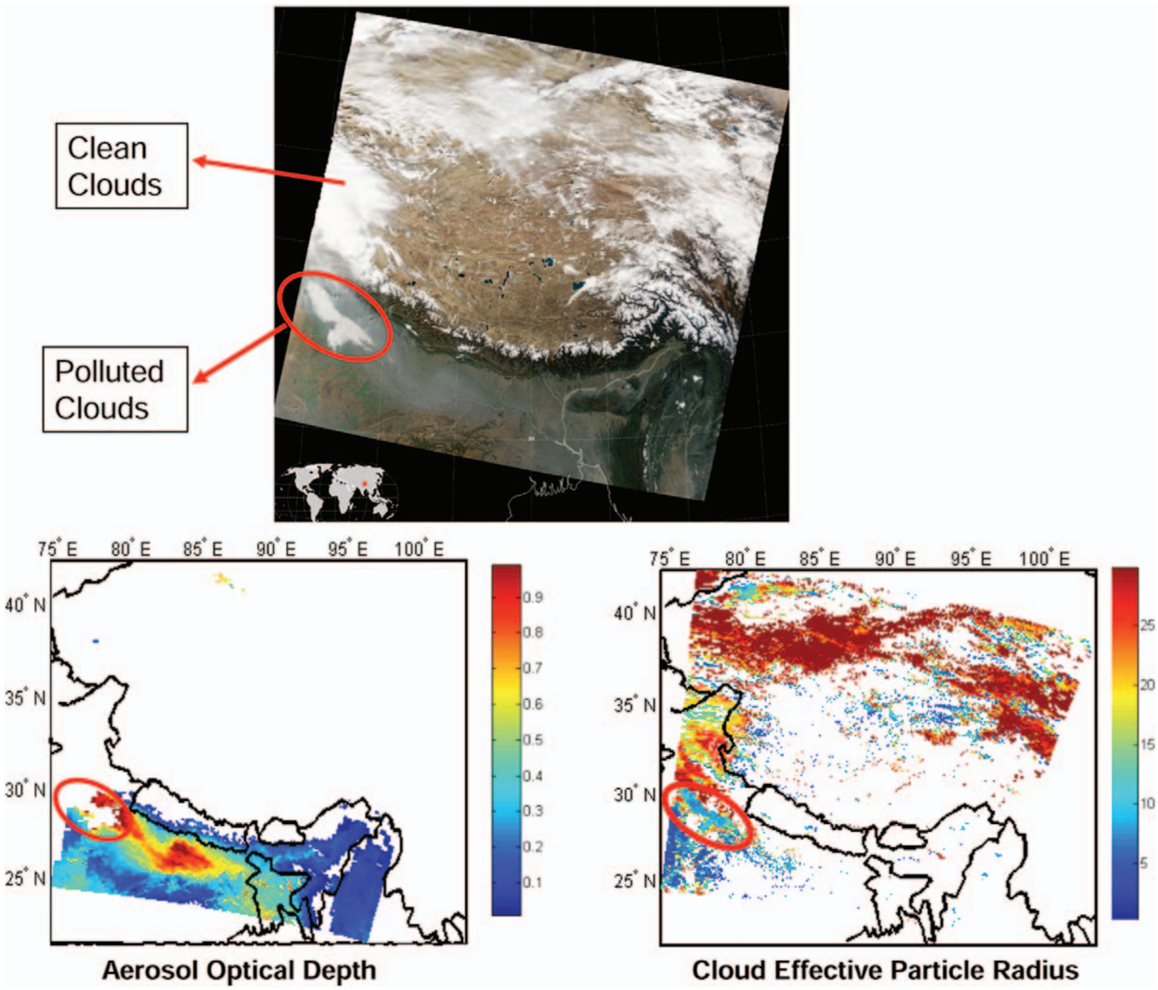

Fig. 4. (top) A true color image of clean and polluted clouds over the southern Tibetan Plateau and the IGP, respectively, taken from MODIS aboard the *Terra* satellite on 28 Dec 2004. The polluted clouds can be easily discriminated against clean clouds by color (polluted clouds have a brownish tinge, while clean clouds are white in appearance). The corresponding (lower right) retrieved effective cloud radius and (lower left) aerosol optical thickness for the clean and polluted clouds in the surrounding regions are also shown.

and Ramanathan (2006) have found that when solar heating by ABC aerosol forcing is imposed alone, it leads to an increase in monsoon rainfall over India. However, when the solar forcing was coupled with observed SST forcing, which included a decrease in north–south SST gradient over the northern Indian Ocean, presumably caused by SDM, they found that the SST gradient effects prevailed, leading to a reduction in monsoon rainfall. However, Lau and Kim (2007), based on numerical experiments carried out with a GCM coupled with a mixed layer ocean, which include both EHP and SDM effects, have found that even on a decadal time scale, the EHP effect prevails in May–June, with increased rainfall over northern India, but the SDM effect becomes more important in July–August, forcing a weakened monsoon.

The aforementioned model results are not necessarily at odds with each other, but rather illustrate the complexity of the aerosol–monsoon interactions that are associated with different aspects of the interaction pathways (see Fig. 1), whose relative importance in affecting the monsoon may be strongly dependent on spatial and temporal scales, and the timing of the monsoon. The results may also differ because they reflect partial response of the monsoon system to a different prescribed forcing. Clearly, these results may be model dependent and need to be treated with extreme caution. We also note that in observations climatic impacts of aerosol on the monsoon water cycle are difficult to detect, because they may be masked or modulated by SST, snow cover, and other land surface changes associated with

El Niño–Southern Oscillation and global warming. The preliminary model results have provided us hints of how the real system may work, as well as the theoretical underpinning and guidance in further data analysis. To increase the reliability of the results, well-designed model experiments by independent modeling groups, including model and observation intercomparison studies, as well as efforts to improve model representation of aerosol–cloud physical processes, are needed.

THE CHALLENGE. In studying the aerosol–monsoon problem it is of the utmost importance to recognize that the monsoon is driven primarily by the evolution of large-scale heat sources and sinks stemming from the seasonal variation of solar radiation and associated land–sea thermal contrast, orographic forcing, latent heat of precipitation, and large-scale dynamics. Preliminary studies outlined in the previous sections have suggested the possibility that aerosol radiative forcing and interaction with cloud microphysics may constitute significant perturbations, especially in the premonsoon seasons or during prolonged break periods, inducing a redistribution of heat sources and sinks through atmospheric water feedback processes, which subsequently alter the evolution of the monsoon. However, understanding of the aerosol effects of the monsoon water cycle is likely to be confounded by natural coupled atmosphere–ocean–land processes, such as El Niño, soil moisture, snow cover, and volcanic eruptions, as well as land use, land change, and anthropogenic greenhouse warming effects, both local and remote. Sorting out the impacts of aerosol forcing of the monsoon water cycle is therefore a very challenging problem.

Over the past decade, significant advances in satellite, airborne, and ground-based remote sensing and in situ observations, as well as climate modeling, have provided an excellent opportunity for the development of a growing number of national and international programs to assess the impact of aerosols on radiation, clouds, and their interaction with the Asian summer monsoon. Yet, up to now, the scientific problems associated with aerosols and monsoons have largely been addressed separately by the aerosol and the monsoon research communities, with the former focused on atmospheric chemistry, radiation, and cloud processes, and the latter on dynamics of the atmosphere and the coupled atmosphere–ocean–land system. To move forward, it is crucial for the two communities to work together and pay special attention to the aerosol–monsoon interface problem.

Recognizing the scientific importance and societal relevance of aerosol and monsoon water cycle variability, various aerosol and monsoon research programs have been spawned at the national and international levels in the past decade and from present through 2010 and beyond. To advance understanding in aerosol–monsoon interaction, it is imperative that a strategy for collaboration in joint aerosol–monsoon water cycle research be developed within and among these programs. For this purpose, the workshop participants recommended *the initiation of a 5-yr (2007–11) Joint Aerosol–Monsoon Experiment (JAMEX) with the objective to unravel the physical mechanisms and multiscale interactions associated with the aerosol–monsoon water cycle in the Asian Indo-Pacific region, aiming at improved prediction of rainfall over Asian monsoon land regions,* through the establishment of a multinational science steering group to

- identify key uncertainties in natural and anthropogenic aerosols in monsoon regions and their interaction with monsoon water cycle dynamics;
- develop a guiding strategy for aerosol–monsoon dynamical system investigations in promoting collaborations between national and international monsoon observational, modeling, and prediction programs;
- coordinate data from satellite, field campaigns, and operational facilities over all of Asia (including deserts, semiarid areas, and monsoon regions) to enable a comprehensive assessment of aerosol–water cycle interactions and impacts;
- develop strategies for data management and stewardship for future aerosol–monsoon research; and
- promote greater scientific synergism between Asian regional aerosol and monsoon research programs through more efficient use of limited resources.

Because the sources of aerosols affecting monsoon regions are located not only over populated areas but also remote regions, such as deserts, high mountains, and heavily forested areas, and because aerosol transport processes are essentially global, satellite observations, in conjunction with well-distributed surface observatories and aircraft sampling, will play an essential role in JAMEX. A critical contribution to JAMEX is the satellite data from the National Aeronautics and Space Administration (NASA) A-train series of satellites, including CloudSat–Cloud-Aerosol Lidar and Infrared Pathfinder

Satellite Observations (CALIPSO), MODIS, Clouds and the Earth's Radiant Energy System (CERES), Atmospheric Infrared Sounder (AIRS)/*Aqua,* and Ozone Monitoring Instrument (OMI)/*Aura,* which take near-simultaneous measurements of aerosol properties, vertical structure, cloud properties, temperature, and water vapor profiles. It is also expected that Tropical Rainfall Measuring Mission (TRMM) will continue to deliver quality precipitation data through the JAMEX period. Because of the need to better define the aerosol forcing functions, in situ and surface-based observations are vital for JAMEX, both for providing input and for validating model simulations and for improving satellite algorithms for retrieving aerosol properties over highly reflecting land surface, such as the "Deep Blue" (Hsu et al. 2004). The development of multisensor algorithms to distinguish aerosols, clouds, and surface reflectance will be a critical component of JAMEX. By combining CERES top-of-the-atmosphere fluxes, aerosol/cloud properties retrieved from MODIS, vertical distributions of aerosols and clouds from CALIPSO–CloudSat, as well as measurements from aircraft and surface network and reference sites as inputs, radiative transfer models can then be used to determine reliably the variation of radiative forcing efficiency of mineral dusts as they move from desert source region to the mixed polluted region. Existing regional observational programs in the Indo-Pacific and Asian regions described in the next section will play important roles in providing ground-based measurements and local logistic support for satellite calibration and validation.

Modeling studies will be crucial in JAMEX in connecting local aerosol and cloud physical processes and in providing understanding of their interactions with the regional and global water cycles (see Fig. 1). In preliminary aerosol–monsoon studies, global chemistry transport models (CTM) combined with satellite data inputs and in situ measurements have played a key role in defining proxies of global and regional aerosol forcing functions for climate models (Chin et al. 2002; Chung et al. 2005; Lau et al. 2006). Since JAMEX emphasizes aerosol–water cycle interaction, the coupling of CTM and dynamical models is essential. JAMEX will require a wide spectrum of modeling hierarchies, including aerosol–cloud microphysics process models, high-resolution (~25 km) weather-resolving global climate models, and very high-resolution regional mesoscale (<10 km) and cloud-resolving models (<5 km) with interactive chemistry, over complex terrain with detailed surface hydrologic processes, as well as coupled ocean–atmosphere processes. Observational data from satellite and field measurements will be used variously for model validation, assimilation, and prescribing model-forcing functions and constraints. JAMEX will leverage on collaboration and partnership with ongoing and emerging national and international programs directly relevant to JAMEX.

POTENTIAL CONTRIBUTING PROGRAMS AND ORGANIZATIONS.[1]

The following national and international programs and organizations have been identified during the Xining workshop as potential contributors or partners to JAMEX.

Asia and Indian–Pacific Ocean Project. China has traditionally very strong and active monsoon

[1] See the sidebar for the lead/point of contact for each program and organization.

POTENTIAL CONTRIBUTORS OR PARTNERSHIPS TO JAMEX.

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Monsoon Asian Hydro-Atmospheric Science Research and Prediction Initiative: Jun Matsumoto, University of Tokyo, Tokyo, Japan
Atmospheric Brown Cloud Program: V. Ramanathan, University of California, San Diego, La Jolla, California, and H. Rodhe, Stockholm University, Stockholm, Sweden
Pacific Aerosol-Cloud-Dust Experiment: J. Stith, NCAR, Boulder, Colorado, and V. Ramanathan, Scripps Institution of Oceanography, University of San Diego, La Jolla, California
East Asian Study of Tropospheric Aerosol: An International Regional Experiment: Zhanqing Li, University of Maryland, College Park, College Park, Maryland
Stations at High Altitude for Research on the Environment in Asia: G. Tartari, Ev-K^2-CNR, Bergamo, Italy
Radiation, Aerosol Joint Observations–Monsoon Experiment over the Gangetic
Himalayas Area: Si-Chee Tsay, NASA, Goddard Space Flight Center, Greenbelt, Maryland
Monsoon Asia Integrated Regional Study: C. B. Fu, Institute of Atmospheric Physics, CAS, Beijing, China

and aerosol research programs supported by the Chinese Academy of Sciences (CAS) and the Chinese Meteorological Administration (CMA). Recently, the Chinese Ministry of Science and Technology (MOST) has approved an ambitious 5-yr (2007–11) national program to study the monsoon coupled atmosphere–ocean–land interaction over Asia and the Indian and Pacific Oceans, focusing on the dynamical effects of heating contrast between the Indo-Pacific warm pool and the Asian continent. The project calls for a special observing period, tentatively planned for 2008–09, with coordinated measurements of atmosphere and ocean from ships, buoys, and moorings over areas from the eastern Indian Ocean, across the South China Sea, to the western Pacific. In conjunction with AIPO, JAMEX will coordinate atmospheric and oceanic measurements with land-based sites, as well as CEOP reference sites, to include meteorological, aerosol physical, and chemical measurements during special observing periods (SOPs).

Aerosol Research Project. Recently MOST approved another 5-yr major national research program aimed at a comprehensive approach to understand aerosols and their climate effects on East Asia under China's National Basic Research Program. The project has the following six major components: 1) acquisition of aerosol physical and chemical properties; 2) remote sensing of aerosol optical properties; 3) emission, transportation, and conversion of major aerosol species; 4) aerosol direct radiative forcing; 5) aerosol–cloud interaction and aerosol indirect effects; and 6) projection of future impacts of aerosols on regional climate. An extensive observation program will be established by integrating various existing networks operated by the CMA and CAS, and an intensive observation campaign is likely to take place in 2008–09. This project is coordinated with the international Sand and Dust Storm (SDS) Project under the World Meteorological Organization (WMO) and the World Weather Research Program (WWRP).

Monsoon Research Program in India. Since the late 1990s, Indian scientists have conducted various national monsoon research programs, for example, the Bay of Bengal Monsoon Experiment (BOMEX)-1999, Arabian sea Regional Monsoon Experiment (ARMEX-I) (2002), ARMEX-II (2003), and ARMEX-III (2005). Particularly relevant to JAMEX are two planned field campaigns, that is, the Severe Thunderstorm Observations and Regional Modeling (STORM)-2006–09, and Continental Tropical Convergence Zone (CTCZ)-2007–2010. The science focus of STORM is in heavy rainfall, lightning, and severe weather. Mesonet (25-km resolution) observation networks will be set up in target regions to monitor heavy rain, wind, lightning, aerosols, and other atmospheric parameters during various phases of the monsoon. In CTCZ, the scientific objective is to unravel the relative roles of internal dynamics and boundary layer forcing of the intraseasonal oscillations in affecting the northward movement of the monsoon from the northern Indian Ocean to the IGP and the foothills of the Himalayas, and their possible relationship to interannual and decadal-scale climate variability and change. The possible impacts of aerosol forcing during the premonsoon period and during monsoon breaks, as well as aerosol–cloud rainfall interaction over the IGP, are additional factors that may affect monsoon predictability. It is recommended that a subprogram within CTCZ be developed to address the aerosol–monsoon interaction problem over the IGP.

Monsoon Asian Hydro-Atmospheric Science Research and prediction Initiative. As a post-GEWEX Asian Monsoon Experiment (GAME) program, MAHASRI is a Japanese-led international program aimed at improving the prediction of the Asian monsoon and its hydrological cycle, focusing on establishing a scientific basis for predicting the hydroclimate of the monsoon system from intraseasonal to seasonal time scale, including developing prediction systems for droughts and flood conditions in regional river basins over Asia. MAHASRI will address issues of diurnal cycles; intraseasonal-, interannual-, and decadal-scale variability and their multiscale interactions with convection and precipitation processes; boundary layer processes; low-level jets; and interaction with complex terrains and the warm water pool. It will target processes in the Asian summer and winter monsoons. Its spatial coverage will include the tropics from the Maritime Continent to South and Southeast Asia, Tibet/the Himalayas, East Asia, and Northeast Asia. Special emphasis will be placed on coupled atmosphere–land–ocean processes, aerosol–monsoon interaction, monsoon rainfall predictability, and flood/drought predictions. MAHASRI will contribute significantly to CEOP and will play an essential role in the WCRP research strategy—the Coordinated Observation and Prediction of the Earth System (COPES). It will contribute to other related international initiatives, such as the Global Earth Observation System of Systems (GEOSS), the United Nations Environment Programme (UNEP), The Observing

System Research and Predictability Experiment (THORPEX), the System for Analysis, Research and Training (START), and the Global Water System Project (GWSP). A special observing period is planned for 2008.

Atmospheric Brown Cloud program. The multinational ABC program is sponsored by UNEP and is aimed at the study of the impacts of aerosols on the regional monsoon and the global physical and chemical system in the Asian monsoon regions and the impacts on regional water supply and agriculture and on human health. It also aims at promoting regional capacity building and in facilitating interaction between scientific and policy-making processes. ABC will work closely with UNEP to translate scientific findings to policy recommendations for action. Long-term aerosol observation sites are planned in the Indo-Asia-Pacific region. Main observatories have been completed in the Indian Ocean (the Maldives), Nepal, including a high-altitude site at 5 km, Japan, Thailand, South Korea, and northern California. These long-term sites will be augmented by coordinated enhanced aerosol measurements, over the China and Japan region during special observing periods, such as EAREX2005. The ABC field measurements have led to a series of modeling and data analysis studies suggesting the importance of the solar dimming effect in affecting the Indian monsoon. ABC has also started innovative aerosol–cloud–radiation measurements from stacked unmanned aerial vehicles (UAV) (www-abc-asia.ucsd.edu/MAC/secure/Index.htm). ABC's planned activities in 2007 and beyond include the increased aerosol observational network over China and deployment of UAVs during field campaigns in Alaska and California in 2007 and a major dust–soot campaign from South Korea in spring 2008. Strong collaboration between JAMEX and ABC will clearly be beneficial to both programs.

Pacific Aerosol-Cloud-Dust Experiment (PACDEX). This experiment has been proposed for spring 2007 and has been approved by the U.S. National Science Foundation. The experiment will be the first Lagrangian study of East Asian dust–soot plume across the Pacific Ocean into North America. It will be conducted by the new NCAR research aircraf—the Gulf 5, and will involve detailed vertical profiling of dust–soot from the lower troposphere to upper troposphere and examine the dust aerosol–cloud interactions for water and ice clouds. PACDEX will document possible impacts of dust and anthropogenic aerosols on mixed- and ice-phase cirrus cloud systems and will be an excellent pilot program ushering in the major pan-Asian activities of JAMEX.

East Asian Study of Tropospheric Aerosol: An International Regional Experiment (EAST-AIRE). EAST-AIRE is aimed at providing better definitions of the origin, physical, and chemical properties of aerosols and improving the understanding of aerosol–cloud and water cycle interaction through long-term measurement over continental East Asia (Li et al. 2007a). EAST-AIRE consists of an expanding network of observation sites measuring aerosol, cloud, radiation, and meteorological variables over diverse climatic zones, including the monsoon heavy rain region in the heart of the Yangzi delta, semiarid and heavily polluted regions in northern China, as well as high-elevation stations in the Qinhai–Tibetan Plateau. Currently, the observational network consists of two supersites with Atmospheric Radiation Measurement program (ARM)-like measurement platforms (Xianghe, Taihu) with more sites to be added, two intensive observing period (IOP) sites in Xianghe and Liaoning Province and more than 25 nationwide sites. Measurement parameters include broadband shortwave and longwave, direct, diffuse, and total irradiance; aerosol optical depth; size distribution; chemical composition; single scattering albedo; cloud cover and optical properties; conventional meteorological variables; and atmospheric trace gases. For more information about the observation sites and parameters, as well as near-real-time data, visit www.atmos.umd.edu/~zli/EAST-AIRE/station.htm. The observation network of EAST-AIRE is extremely important in JAMEX in providing aerosol–monsoon water cycle observations downstream of the IGP and Tibetan Plateau region, for satellite data calibration, empirical data analysis, and modeling studies.

Stations at High Altitude for Research on the Environment in Asia (SHARE–Asia). The Himalaya–Karakoram Range represents a unique observation perspective for the study of elevated aerosols, long-range transport, and monitoring the regional-scale consequence of climate change associated with the monsoon circulation. Recognizing this, the Ev-K^2-CNR Committee (as part of the Italian National Research Council) has launched the SHARE-Asia initiative for development of an integrated system of physical, chemical, and meteorological measurements to increase scientific knowledge on climatic and pollution-related processes, and in facilitating local capacity building to mitigate the adverse impacts of global change and environmental degradation in mountainous regions. SHARE-Asia currently includes the Pyramid MeteoNetwork (PMN), a climatic network founded in the 1990s, comprising six stations (2660–5050 m) in Nepal's Sagarmatha National Park (SNP), and two stations (3015–3925 m) in Pakistan on the Baltoro Glacier. In February 2006 the "ABC-Pyramid Laboratory" (5079 m) was installed in SNP as part of the ABC monitoring stations. ABC-Pyramid is a component of the SHARE-Asia network, as well as the monitoring activities developed for CEOP, International Global Atmospheric Chemistry (IGAC), Global Atmospheric Watch (GAW), and Global Land Ice Measurements from Space (GLIMS). The SHARE sites, together with the observations sites Cum-Cuo Lake and Lhasa in Tibet, offer unique high-altitude observations of aerosol concentration that are critical for JAMEX.

Radiation, Aerosol Joint Observations–Monsoon Experiments over the Gangetic Himalayas Area (RAJO-MEGHA). RAJO-MEGHA (dust cloud in Sanskrit) is a grassroots science initiative organized by the NASA Goddard Laboratory for Atmospheres with the objective to determine the role of dust aerosols with regard to elevated heat sources around the Tibetan Plateau and Himalayas region and the interaction with anthropogenic aerosols in the IGP in affecting the climate and water cycle of the South Asian monsoon. RAJO-MEGHA will focus on integrated long-term monitoring, field observations, and the modeling approach used to study the aerosol–cloud–precipitation and large-scale monsoon dynamics interaction. Three major components of RAJO-MEGHA are planned. First is the upgrade and standardization of aerosol measurements in various sites in China, India, and possibly Nepal, via the global Aerosol Robotic Network (AERONET). Many of these sites coincide with the CEOP reference sites, for example, Lhasa, Lanzhou, and Tibet. Second is a field campaign, possibly in 2009–10, in collaboration with Indian scientists in the IGP, in conjunction with planned activities of the Indian national monsoon program (see section "Monsoon Research Program in India"). Third is a NASA satellite, that is, CloudSat–CALIPSO, calibration and validation pilot activity to be conducted with the JAMEX field campaign in 2008–09 and observing platforms of EAST-AIRE and ABC, but covering the broader Asian monsoon region, as well as the semiarid and desert regions in northern and western China. This activity will also be coordinated with modeling efforts of the NASA Modeling and Analysis Program (MAP).

Monsoon Asia Integrated Regional Study (MAIRS). MAIRS is sponsored by the Earth System Science Partnership (ESSP) with the objective to better understand the role of human activities in affecting and interacting with the changing atmospheric, terrestrial, and marine environments in the Asian monsoon regions and to develop an institutional capacity to improve forecasts and to mitigate adverse impacts. MAIRS will address, among others, issues related to ABC, potential impacts of black carbon on mountain glacier and snow melt, and health-related issues of air pollution. Monitoring stations for aerosol, agriculture, and biodiversity will be set up in coastal zones, high mountains, semiarid regions, and urban areas in the Southeast and East Asian regions.

INTERNATIONAL COLLABORATION: THE ROLE OF CEOP. CEOP, a GEWEX/WCRP program and a first element of the Integrated Water Global Cycle Observations (IWGCO) in 2001, was established to integrate current and planned earth observing satellites, operational satellites, in situ observations, and modeling assets of the GEWEX continental-scale experiments and field observations to support key science objectives in climate prediction and monsoon system studies (Koike 2004). At the completion of Phase I (2002–05), two full annual cycles (2003–04) of research-quality datasets from satellites, reference sites, and model output location time series (MOLTS) have been processed and made available for data analyses and model validation studies. Phase II (2006–10) will continue the data collection and processing, while providing increasing focus on scientific research using CEOP data and coordination with planned observational and modeling programs. In Phase II, the CEOP Inter-Monsoon Study (CIMS) will focus on new science thrusts on aerosol–monsoon water cycle interactions (Koike 2004), and U.S. contributions to CEOP are being coordinated (Lawford et al. 2006).

CEOP will provide a prototype of the international framework that can provide the science oversight, data policy, collaboration, and partnership with national organizations that will be needed for JAMEX. Currently, more than half of the CEOP reference sites are in the tropics and many reside in the Asian monsoon region (for detail, see the CEOP Web site http://monsoon.t.u-tokyo.ac.jp/ceop/). As such, there are still large scientifically critical areas within the Asian monsoon region that do not yet have a reference site set up. In conjunction with JAMEX, CEOP can provide the international science and organization context for setting up additional stations and/or enhance measurement scope and capabilities in India and China, including the Tibetan Plateau, to monitor the sources and transport of aerosols. As a first step, the global AERONET of the surface sun photometer and ancillary measurements network (Holben et al. 1998), as well as the MicroPulse Lidar Network (MPLNET) of relatively low cost micropulse backscatter lidars that measure the vertical profile of aerosols (Welton et al. 2001) should be included as part of the JAMEX/CEOP-II database. Others, such as the Asian Dust Network (ADNET), which observes dust outbreak over East Asia, should also be included. In addition, JAMEX/CEOP should be coordinated with the IWGCO and emerging pan-CLIVAR/GEWEX monsoon modeling initiative and as a contribution to the WCRP/COPES. In focusing on aerosol–monsoon interactions, JAMEX will address important scientific issues and crosscuts that enhance the interaction between GEWEX and CLIVAR.

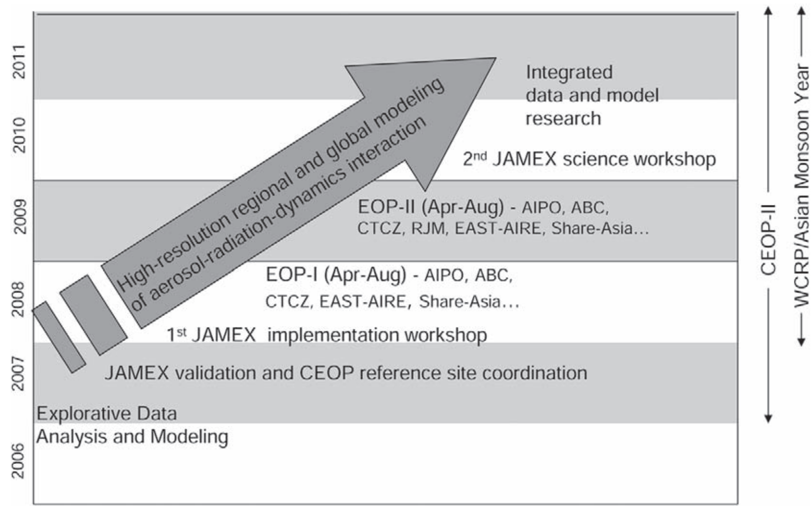

Fig. 5. Proposed time schedule for JAMEX.

The Xining workshop is an example of international organization, such as CEOP, in enabling the coordination of diverse international scientists and government representatives to focus on a new approach on joint aerosol–monsoon research. At the workshop, representatives from various national and international programs presented scientific findings and program plans that are now adopted as core science themes and organization framework for JAMEX.

TIME SCHEDULE FOR JAMEX. JAMEX will be planned as a 5-yr (2007–11) international aerosol–monsoon research project aimed at promoting collaboration, partnership, and alignment of ongoing and planned national and international programs. The tentative time schedule, including milestones and research activities, is shown in Fig. 5. Two coordinated SOPs, covering the premonsoon (April–May) and monsoon (June–August) periods, are tentatively targeted for 2008 and 2009. The major work on validation and reference site coordination will take place in 2007 through the spring of 2008. A major science workshop is planned after SOP II in 2010. Modeling and satellite data diagnostic studies will be crucial in the design of the observation arrays and measurement platforms for SOPs. A series of international workshops has been organized in 2007 to plan and coordinate various international and national efforts relevant to JAMEX. Advanced modeling and satellite assimilation studies will be carried out throughout the entire JAMEX period.

In addition to the observation networks and programs previously mentioned in this document, other planned activities are relevant to JAMEX, including the Progress in Aerosol Retrieval and Assimilation Global Observing Network (PARAGON), which provides integrated observations of aerosols (Diner et al. 2004) and the National Aerosol-Climate Interaction Program (NACIP), which oversees aerosol–climate research in the United States. To better understand the water cycle processes and their agents of change vis-à-vis climate change impacts in monsoon regions, aerosols processes and monsoon dynamics need to be studied synergistically. JAMEX needs to be coordinated with the aforementioned aerosol and water cycle observation networks and national research programs to maximize the use of existing observations, both satellite and in situ, and to formulate a common strategy for model validation and improvement. An international science planning group consisting of lead scientists and/or point of contacts for the aforementioned major aerosol and monsoon programs, as well as other relevant programs, should be formed as soon as feasible under the auspices of CEOP or a multinational body to develop a more detailed road map for JAMEX.

CONCLUSIONS. Thanks to the advent of satellite, aircraft, and in situ observations and advanced Earth system models, great strides have been made in aerosol and monsoon research in recent years, as separate disciplines. There is now a growing body of evidence suggesting that aerosol and monsoon water cycles may strongly interact. Because of the profound societal impacts of air pollution and monsoon floods and drought, countries in Asia and adjacent regions have committed major national resources to aerosol and monsoon research. The time is now ripe for an international joint effort in aerosol and monsoon research. JAMEX is proposed as a first step toward a synergistic approach in aerosol–monsoon research leveraging on various planned national and international programs. It is aimed at providing better understanding and improved predictions of aerosol–monsoon water cycle variability that will help governments and stakeholders to make informed decisions in mitigating societal impacts caused by natural and man-made aerosols and monsoon floods and droughts. JAMEX will coordinate and stimulate aerosol–monsoon water cycle research, through planning and conducting coordinated pan-Asian observations in 2008–09 of aerosol properties, and transport processes, together with atmospheric and oceanic measurements, complementing ongoing monsoon research in GEWEX, CLIVAR, and IGBP under WCRP. During the writing of this article, JAMEX has been endorsed as an integral component of the WCRP Asian Monsoon Years (2007–11) initiative. The objective of AMY is to coordinate the burgeoning monsoon and aerosol observation and research activities in Asian monsoon countries and to plan for continued enhanced observations beyond 2009, with possible extension to an International Monsoon Year (IMY) project, to include monsoon regions of Australia, Africa, and the Americas. This is an important development vital to the international coordinating efforts and success of JAMEX.

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